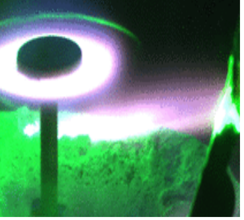

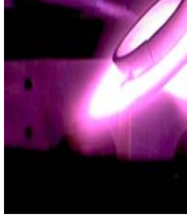

Dusty Plasma Solar Sails

Robert Sheldon
NASA Faculty Fellowship Program
August 15, 2003

Acknowledgments

- Dennis Gallagher
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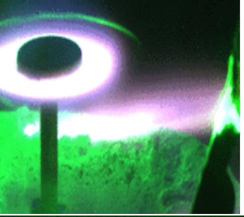
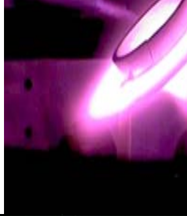
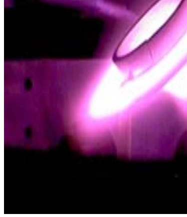
- My supervisor
- PI on plasma sails
- My transportation and captive audience
- My favorite critic
- Dust theorist
- Championed my cause
- Did much of the labor

Can Ultralight Solar Sails be made of Dust?





Talk Overview



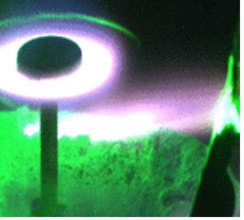
- Review of Solar Sails Physics
  - At the risk of boring some of you, let me repeat what we know about rocket science.
- Reassessment of Dusty Plasma Sail
  - We use our laboratory results to extrapolate the effectiveness of a dusty plasma sail
- Review of Plasma Sail Proposal
  - This has been a frequently misunderstood topic, that I hope I can clarify some

The Rocket Equation

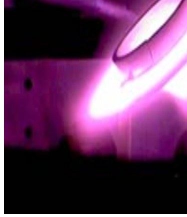
$V_{exhaust} = I_{sp} * g$ [d/dt(MV) = 0]

$dV = V_{exhaust} * \log(\text{final mass} / \text{initial mass})$

Material	Isp	Limitation
Solid fuel	200-250	mass-starved
LH2/LOX	350-450	mass-starved
Nuclear Thermal	825-925	mass-starved
Clean Nuclear	~1000	
MHD	2000-5000	energy-starved
Ion	3500-10000	energy-starved
Matter-Antimatter	~1,000,000	mass-starved
Photons	30,000,000-∞	both-starved



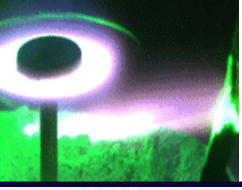
Fast Pluto flyby?



Voyager=16 years to Pluto. A 1.6 year trip would take dV = 5.8e12m/5e7 s ~100 km/s

Isp	M_rocket/M_payload
100,000	1.1
10,000	2.7
1,000	22,000
400	72,000,000,000

We aren't going to use chemical rockets if we want a fast Pluto flyby larger than a pencil eraser.



How do solar sails work?

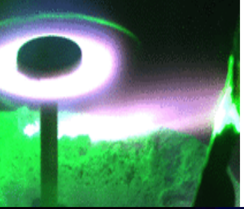
Momentum of photon = E/c, if we reflect the photon, then dp = 2 E/c. At 1 AU, E_sunlight=1.4 kW/m^2==>9μN/m^2=9μPa

Then to get to Pluto in 1.6 years, we need ~0.004 m/s^2 of acceleration. To get this acceleration with sunlight we need a total mass loading of <2gm/m^2 !

Mylar materials ~ 6 gm/m^2

Carbon fiber mesh < 5 gm/m^2 (3/2/2000)

We are getting close!



Issues in Solar Sails

- **Mass loading of reflective foils**
- **Albedo or reflectivity of thin foils**
- **Deployment of thin films**
- **Extra mass of booms, deployers, etc**
- **Survival of thin films in hostile environment of UV, flares, particle radiation, charging**

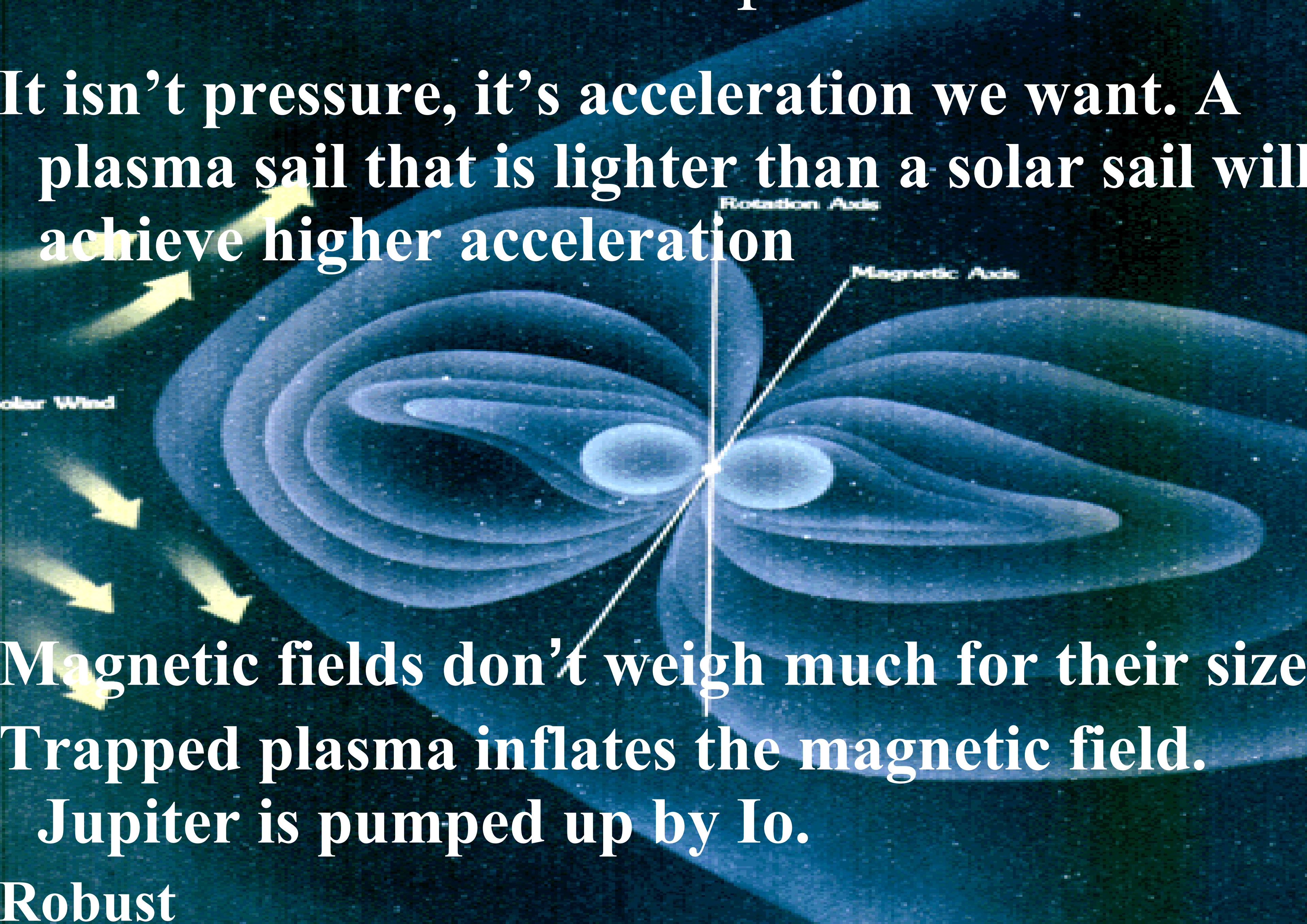
packageability, areal density, structural stability, deployability, controllability, and scalability...strength, modulus, areal density, reflectivity, emissivity, electrical conductivity, thermal tolerance, toughness, and radiation sensitivity." Gossamer AO

What About The Solar Wind?

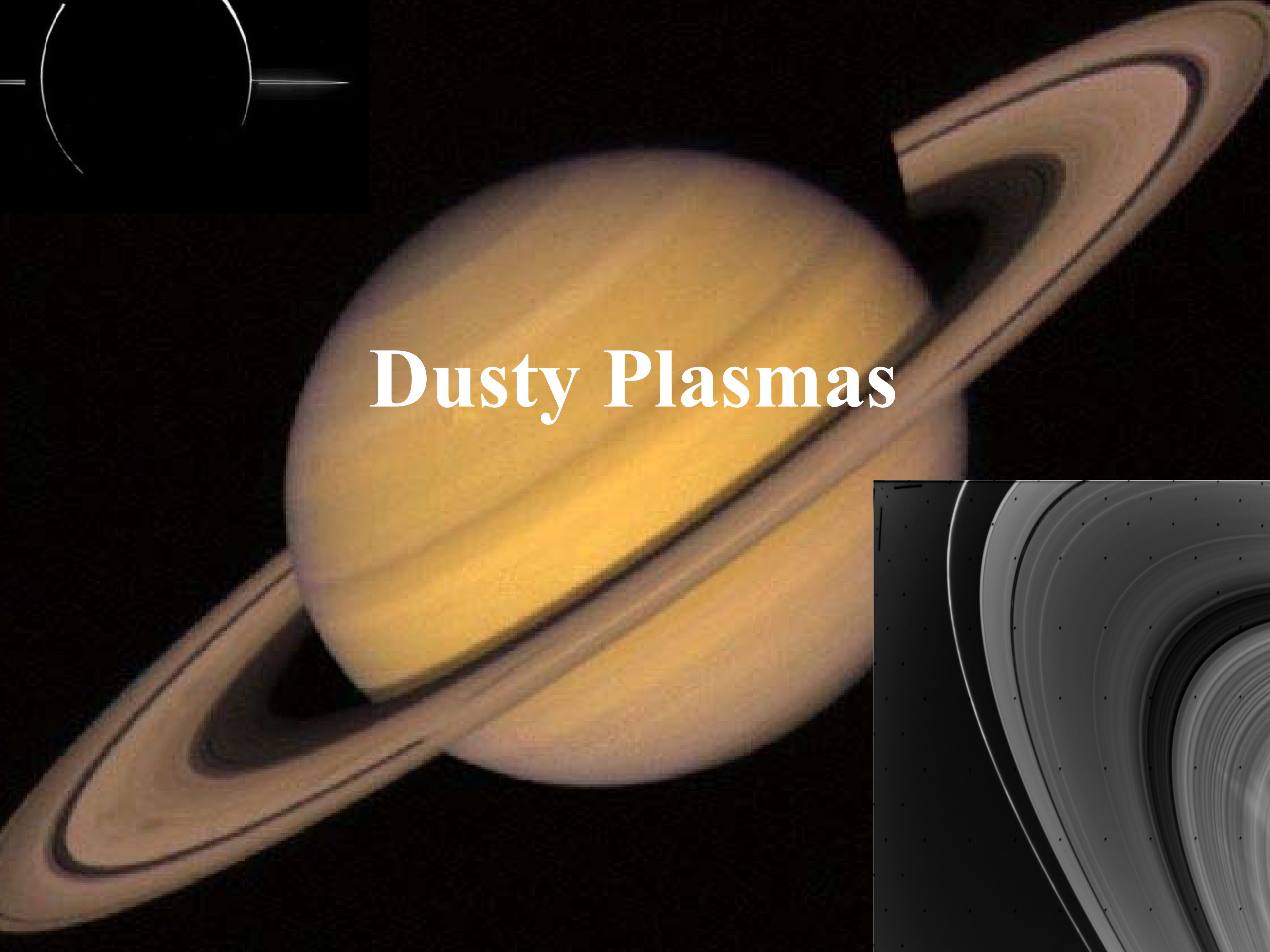
- **Solar wind density = 3/c**
  H^+ at 350-800 km/s
  - **H^+ Flux thru $1m^2/s$= $1m^2*400km*3e6/m^3$=1.2e12**
  - **Pressure = 2e27kg*1.2e12*400km/s =**
    1nPa
- **That's 1/1000 the pressure of light! No thrust?**
- **But Jupiter's magnetic size is HUGE =size of full moon.**

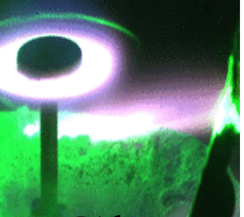
Plasma Sail Capabilities

- It isn't pressure, it's acceleration we want. A plasma sail that is lighter than a solar sail will achieve higher acceleration
- Magnetic fields don't weigh much for their size
- Trapped plasma inflates the magnetic field. Jupiter is pumped up by Io.
- Robust



Dusty Plasmas

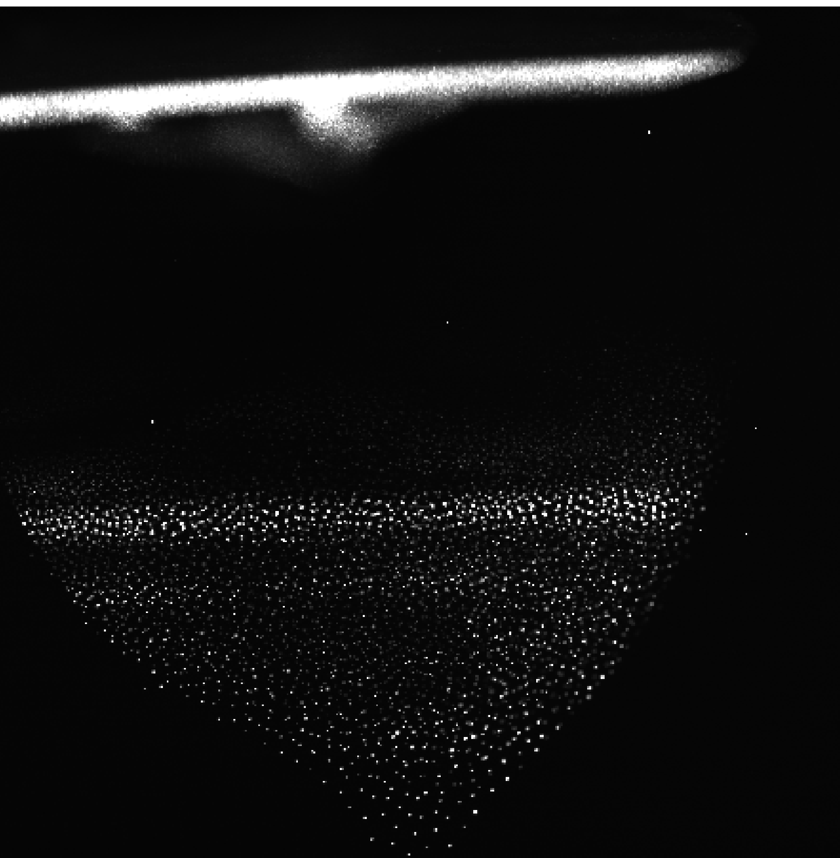




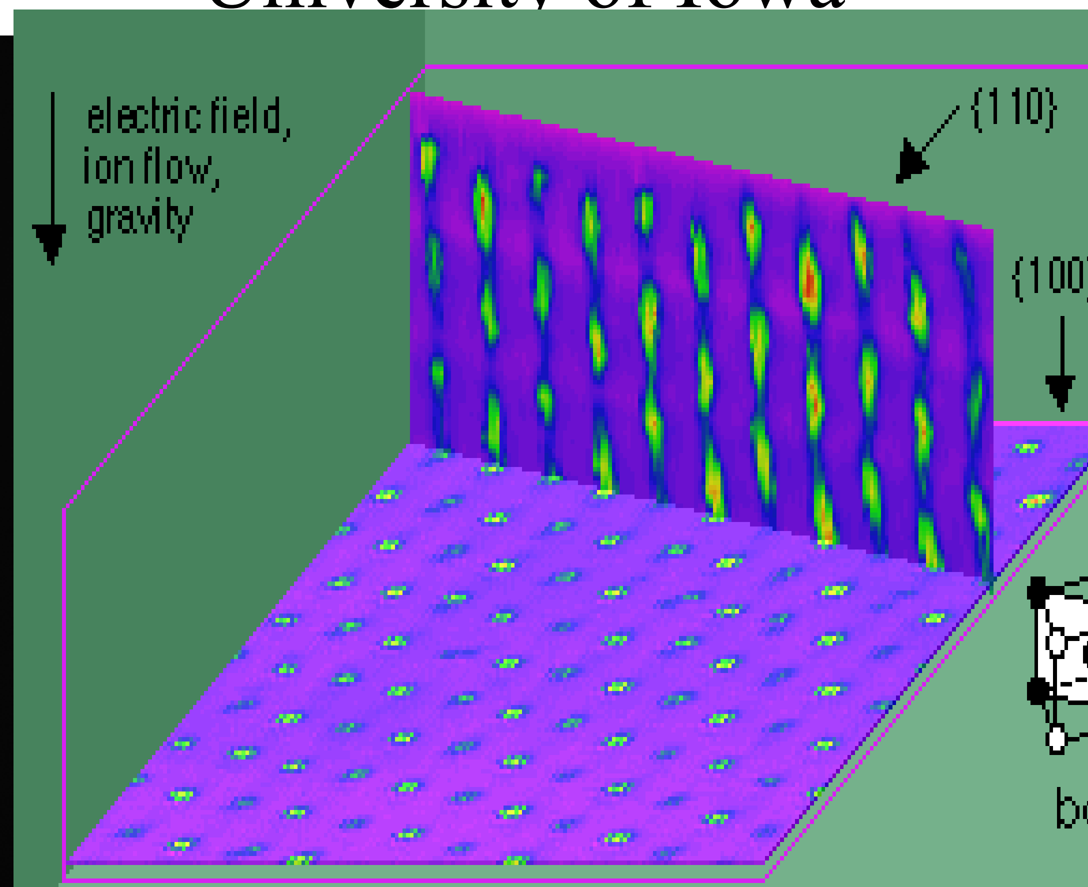
What is a dusty plasma?

- Charged dust + plasma = a "plum pudding" Coulomb crystal, or as Cooper-pairs in BCS theory. Note surface tension & crystalline interaction.

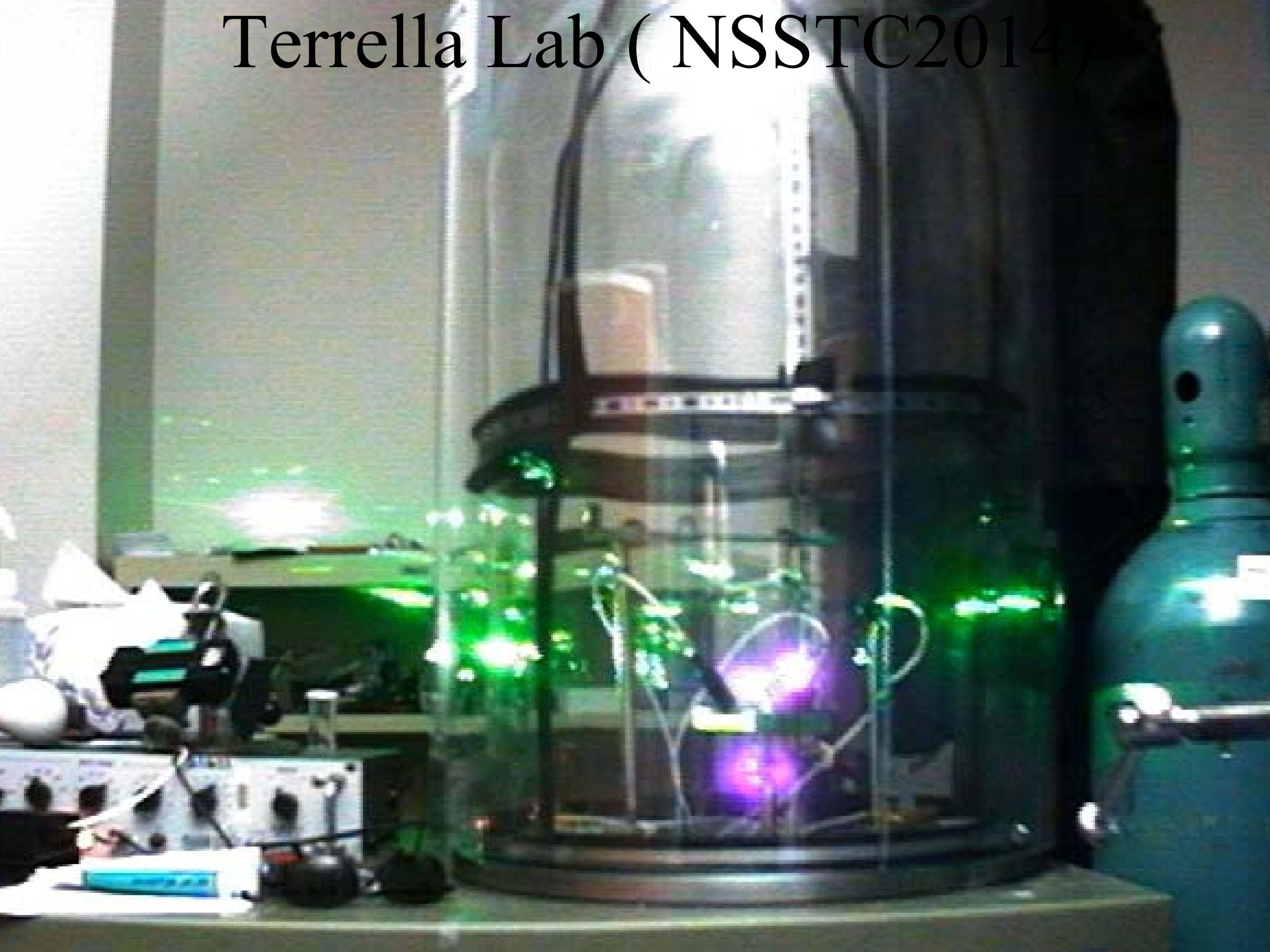
Auburn University



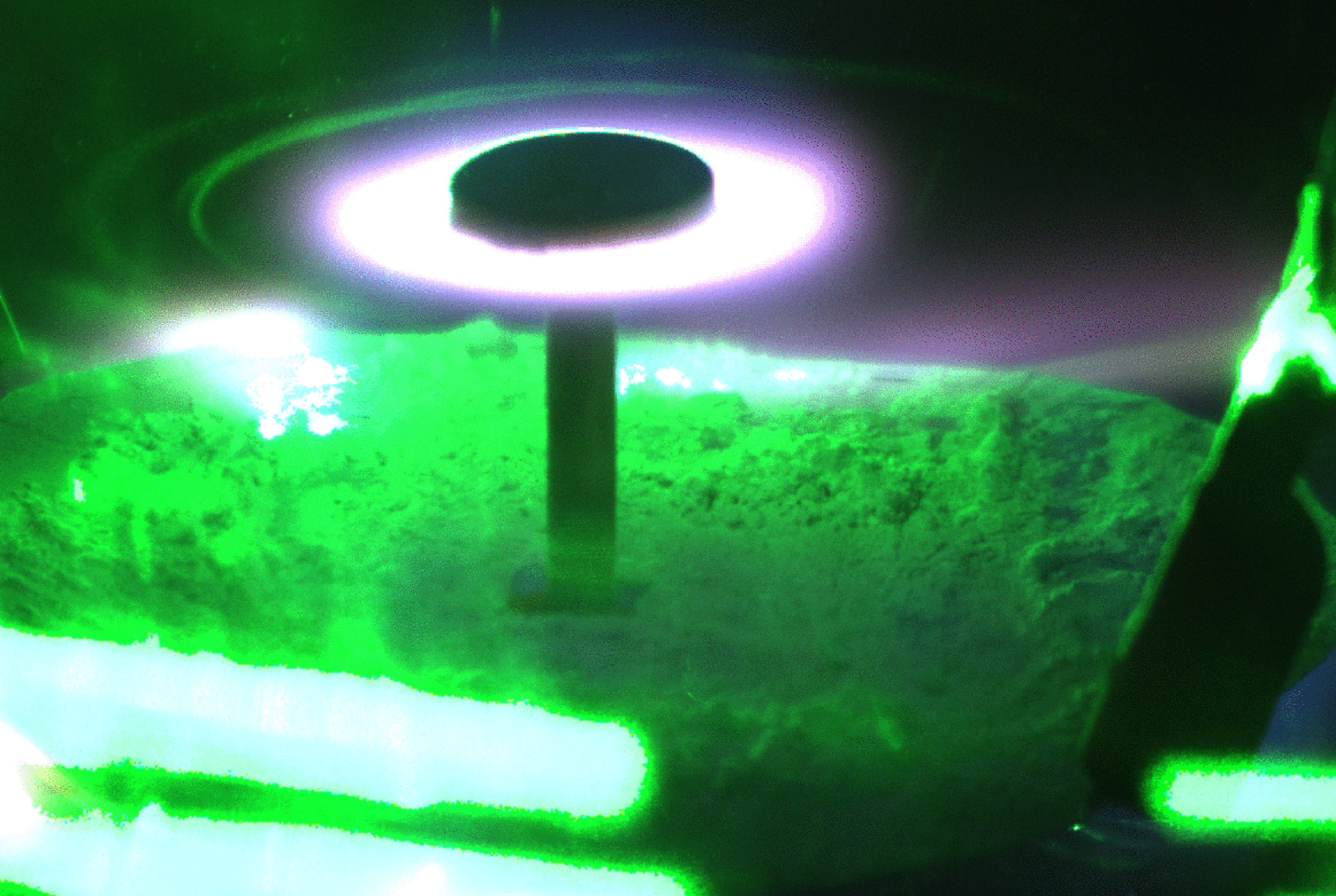
University of Iowa

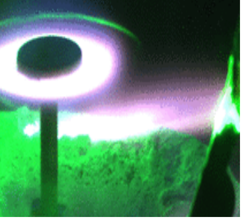


Terrella Lab (NSSTC2014)



Levitating Dusty Plasma w/ Magnets





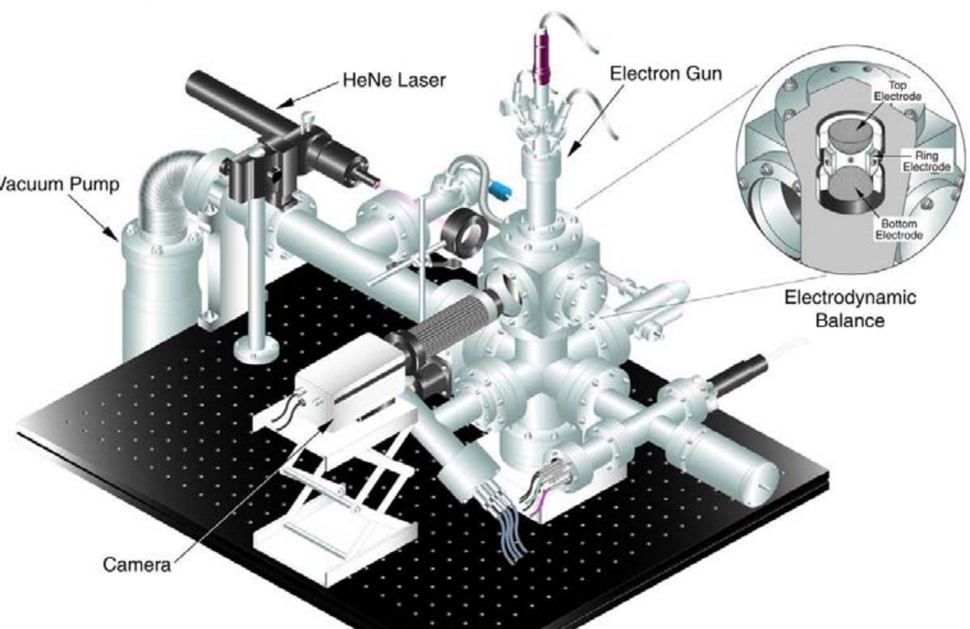
The Dust Trap

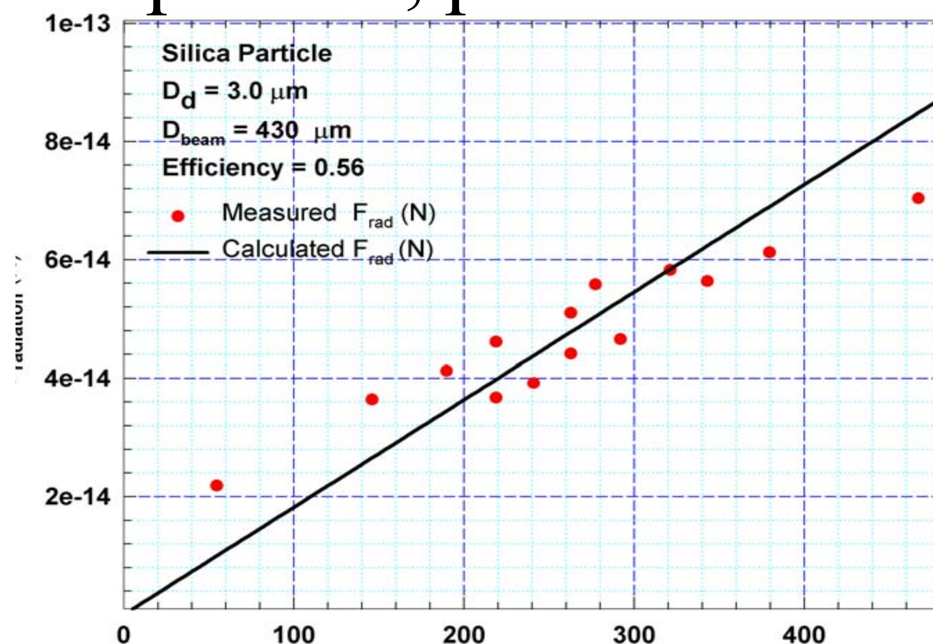
Arc discharge on 3μ SiO_2 dust grains charges them negative. Probable charge state on dust is -1000 e/grain.They are trapped in a positive space-charge region adjacent to ring current. The RC is formed by -400V DC glow discharge on NIB magnet, streaming electrons ioniz the air, maintain the RC. Phase-space mismatch of streaming electrons and trapped ions produces the space charge. Highly anisotropic B-field contributes as well. We are presently attempting to map out the potential with Langmuir probe. Initial attempts were inconclusive, both because of the speed of a manual scan, and the limited tir to leave discharge on before magnet heat up beyond the Curie temperature and demagnetizes

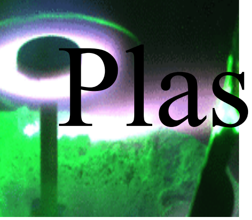
Langmuir Probe mapping

Smaller Dust?

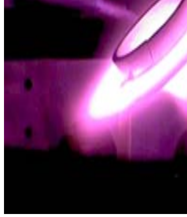
e dust mass goes as R^3, whereas the dust area goes as R^2
hat is the smallest dust that still transfers momentum?
e've done the first light pressure on dust experiments usi
O_2. If a disk absorbs all the light incident on it, the
omentum p=E/c. If it reflects, p=2E/c. We used 532nm
ht, and found that down to 500nm radii, the dust behave
dway between a black and white particle, p~1.5 E/c







Plasma Losses



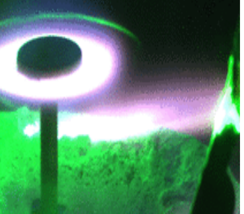
Even if the dust is stationary, won't the plasma keep hitti the magnet? Can we reduce the plasma losses?

– Yes, if the magnet is toroidal, then the field lines don't hit the magnet. This is Winglee's geometry. But the plasma density goes up. (I'm taking bets about whether dust collects there)

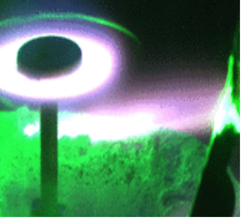
If the magnetic field scales with magnet radius, but the weight of the magnet scales with the cube of the radius, how can we achieve large magnet strengths?

– Toroidal magnets increase the radius without paying the cost increasing the volume (as much).

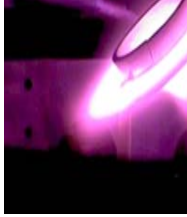
Will a toroidal magnet still have the same trapped plasm geometry?



Toroidal Magnetic Trap (jets)



Dust Thrust



Assume:

- 1μ diameter dust grains, density=1g/cc (Carbon?)
- 200 e/dust grain (EUV photoemission charging)
- Ni at spacecraft=1e12/cc, drops as 1/R
- RC lies ½ distance to edge of bubble=5-5.5 km,
- Dust ring is 1 meter thick (diameter of magnet)

Then quasi-neutrality requires: Qd Nd < Ni, so Nd~Ni/Q=1e5/cc, => 8% opaque, 2.3% bubble area

Sunlight = 1μPa, Solarwind = 1nPa, so dust adds: 0.08*0.02*1000 = 190% to geometric solarwind thrust.

For 15km radius sail ==> 1.4 N of thrust with 260 kg

Mission Scenarios

Assume:

magnet, gas & s/c = 500 kg + dust = 760kg

Initial acceleration = 1.4 N/ 760 kg = 0.0018 m/s^2 ~ $5g/m^2$

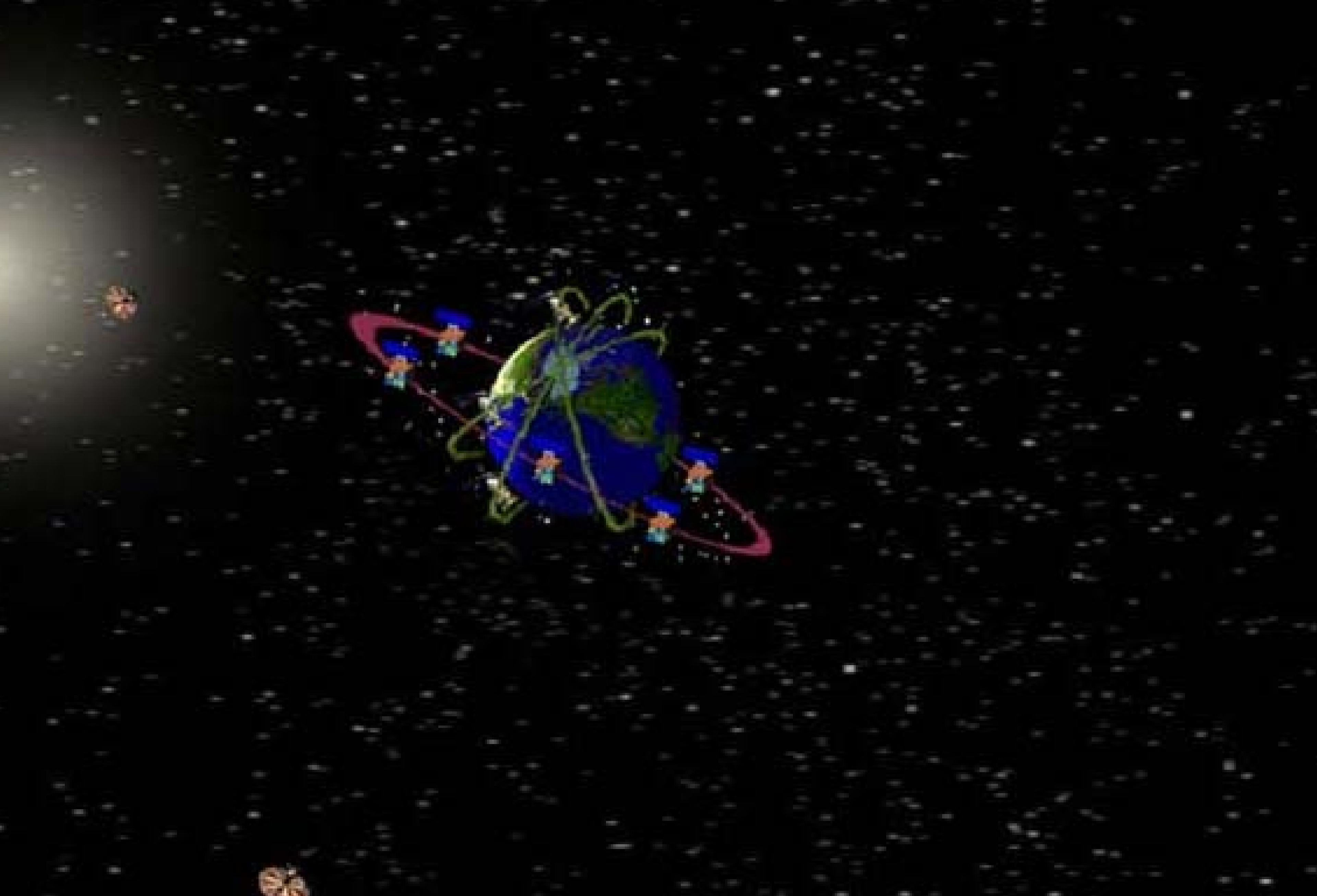
Use $d = ½ at^2$ to estimate trip time (overestimate of course)

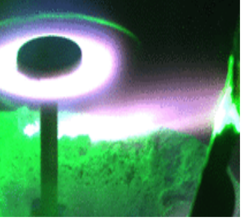
Then ~300 days to Jupiter. Contrast with Voyager, 721kg, ~700 days to Jupiter. That's only slightly better, and at Jupiter we would need a non-solar array power source. Since sunlight power goes as $1/R^2$, solar sails ge more attractive for R < 1 AU, that's where they shine.

"Polesitter" $R = (mg/F)^2$ = 73 Re (better than L1)

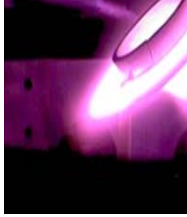
Solar storm monitor, $R = (1 – F/m\omega^2 Re)^{1/3}$ = 0.88 AU

Solar Sail missions





The Plasma Trap



We've shown that plasma can hold dust.

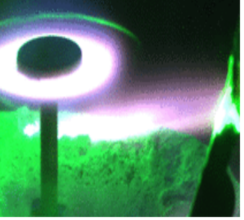
The dust is distributed in a ring around the magnet

What is the size of this dust ring sail?

– *Depends on the size of the plasma ring current, which depen on the size of the plasma bubble.*

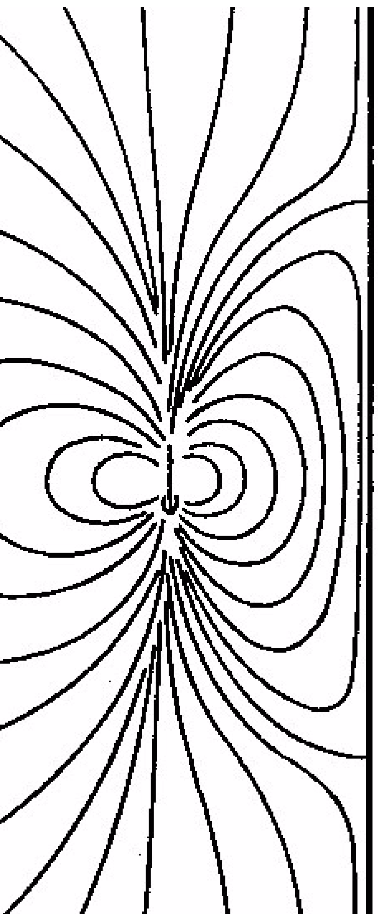
Winglee argues that it is possible to make 30km bubble in the solar wind. What is the feasibility of that for dust plasma?

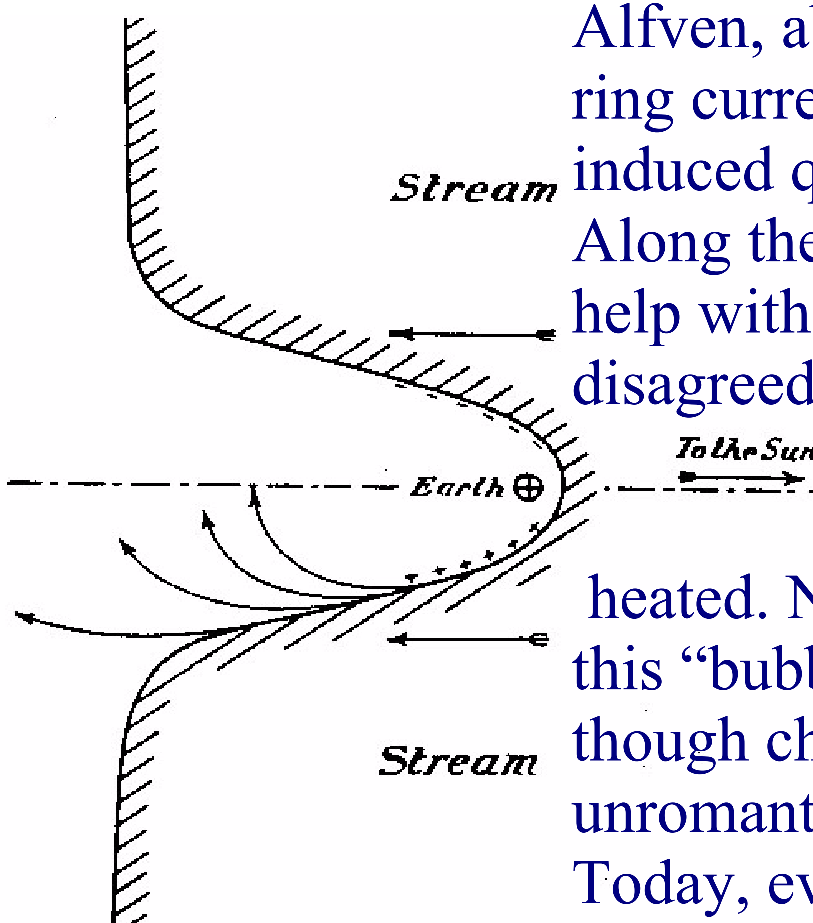
– *The debate gets bogged down in details of plasma physics ar magnetic field scaling. As a starting point for discussion, we plasma-free plasma physics to achieve ballpark estimates.*



Magnetic Bubble Memory

laxwell, 1865, showed that a dipole next to a conducting plane would be onfined, as if an image dipole were behind the plane. Chapman, 1932, used is argument to say that a plume of plasma from the sun would wrap around e earth, forming a bubble. Somehow, he thought, a ring current would form

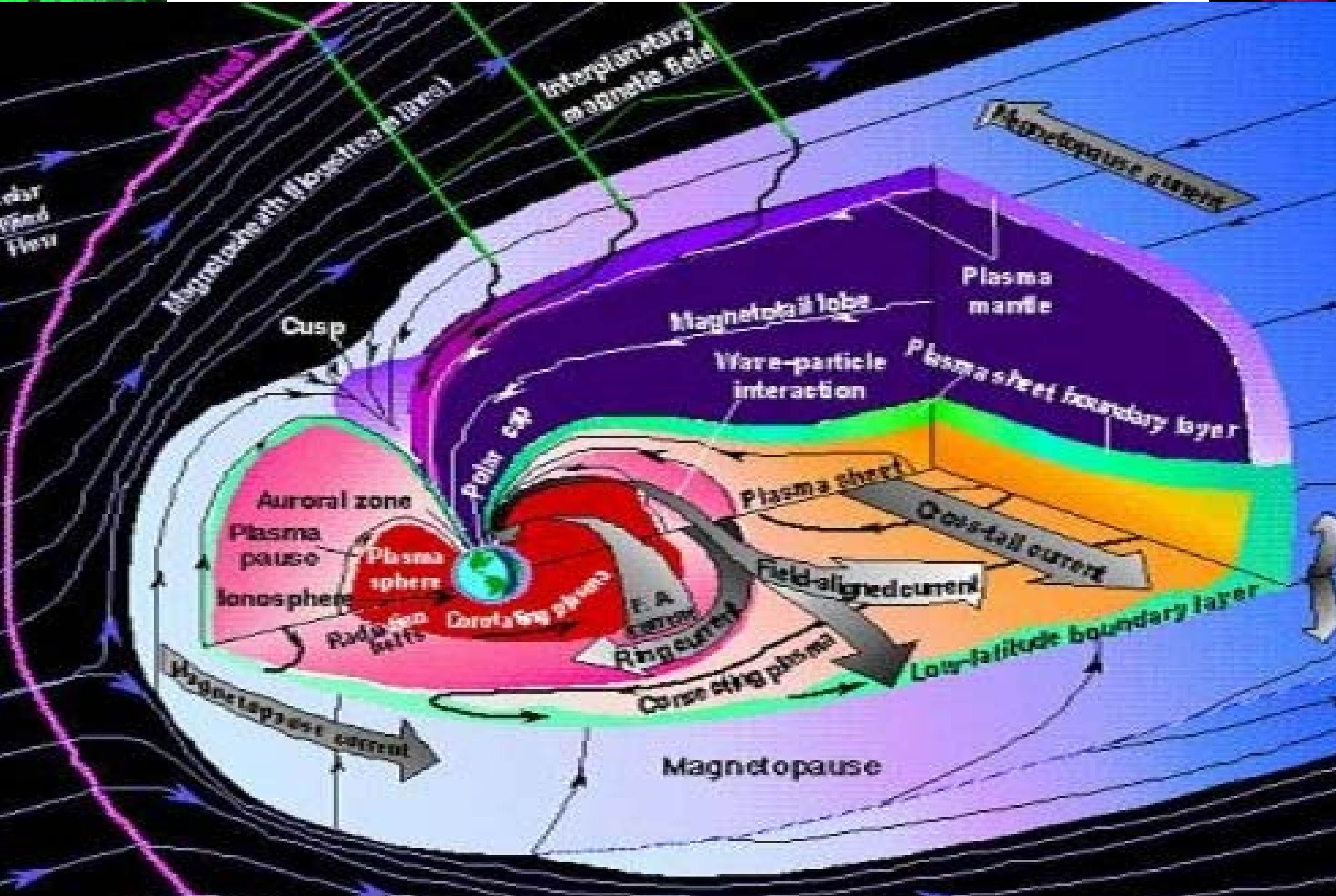




Alfven, about 1945, argued that th ring current would form due to induced qv x B forces on electrons Along the way he invented MHD t help with the debate. Chapman disagreed, and the debate got very

heated. Not until the space era did this "bubble" begin to be understoo though christened with the unromantic name Magnetosphere. Today, even this specialization is

Modern Magnetospheres



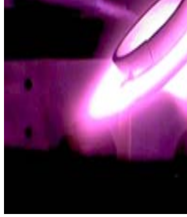
Gross Simplification

In hydraulics, there's one basic way to move machinery,
fluid pressure. In MHD we've added a 2nd way, magnets
So to create a bubble in magnetized solar wind to hold o
plasma, we can either use plasma fluid pressure or
magnetic pressure.

What is the magnetic pressure (Energy/Vol=Force/Area
It is the $|B|^2$ created by the current systems + magnets.

As it turns out, when the plasma pressure is greater than
the magnetic pressure, $\beta = 8\pi nkT/B^2 > 1$, all sorts of fluid
instabilities crop up. So we assume $\beta=1$. Then the plasm
doubles the magnetic pressure, and we only calculate
magnetic pressure alone and scale: $B = B/\sqrt{2}$

Bubbles without Plasma



larwind sails have been proposed
thout plasma or RC, called “magsails”.
ne problem is one of size. Since
larwind pressure is 1/1000 of photon
essure (at all locations since they are
th $1/R^2$ scaling), one needs a bubble 30
nes larger than a lightsail to get the same
rust.

pole $B = B_0 (R_0/R)^3$. So for R=30km
bble with “nose” B=50nT (as at Earth),
e can calculate either B_0 or R_0. If we set
o=1m (to fit it in a rocket faring) we get
o=170,000 T. If we set Bo=1T (possible
th NIB magnets) we get a Ro=55m.
o BIG! Even w/ superconducting mag

Bubbles with Plasma

Robert Winglee published in JGR 2000 a computer simulation that suggested plasma would carry a current that made the magnetic field much stronger, B = B_0(R_0/R
Extrapolating from his 2m simulation, he predicted 30kn
could be made easily with existing technology.

We calculate B=35nT, R=15km bubble gives:

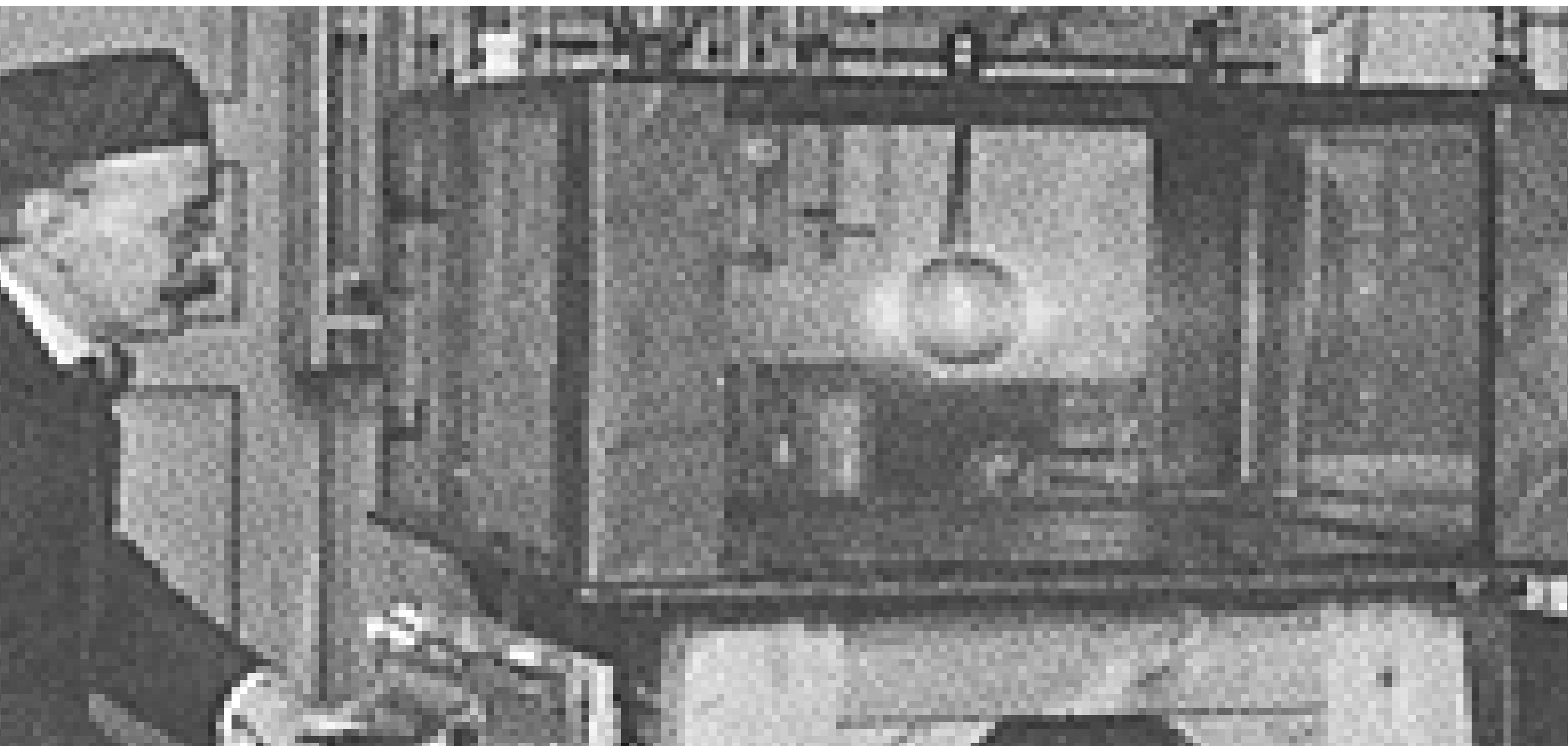
– Ro=1m => Bo=5.2mT
– Bo=1T => Ro=0.52mm.

If bubbles were this easily formed, there isn't a spacecraf
up there that has ever measured the solar wind!

What physics can improve this estimate? What is the
nature of the plasma currents? Can we model them bette

Bubble Current Systems

e actually know a lot about plasma currents + magnets.
904 Kristian Birkeland bombarded a model of the Earth'
agnet (terrella) with electron beams.



Ring Current = Mag Pressure

ng Current (RC) is THE way plasma makes magnetic currents (or pressure).

- Plasma is “diamagnetic”, when you put a magnetic field on it, rearranges itself to “short out” the magnetic pressure. This is j Lenz' Law, that nature responds to change by minimizing the energy. We can see this in the RC as the production of a magnetic field INSIDE the RC that neutralizes the magnetic field. In Chapman's picture, this RC exactly cancels the B-fiel
- Plasma as a fluid flows to the lowest pressure region. The dipo equator is the lowest magnetic pressure region.
- Plasma survives when source rate > loss rate. The dipole equa is the smallest loss rate due to pitchangle scattering.
- RC enhances B-field OUTSIDE the RC, expanding the bubbl

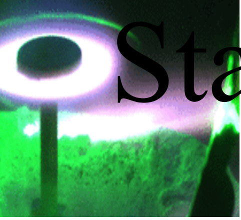
Ring Current Math

Everybody loves a current ring: www, Halliday&Resnick, Jackson, ... We have semi-analytic solutions.

- Elliptic integrals. The series doesn't converge outside the RC nor anywhere near the RC.
- Analytic approximation to elliptic integrals. Poor representati
- Spherical harmonics. OK, but poor convergence near the ring
- Bessel functions.

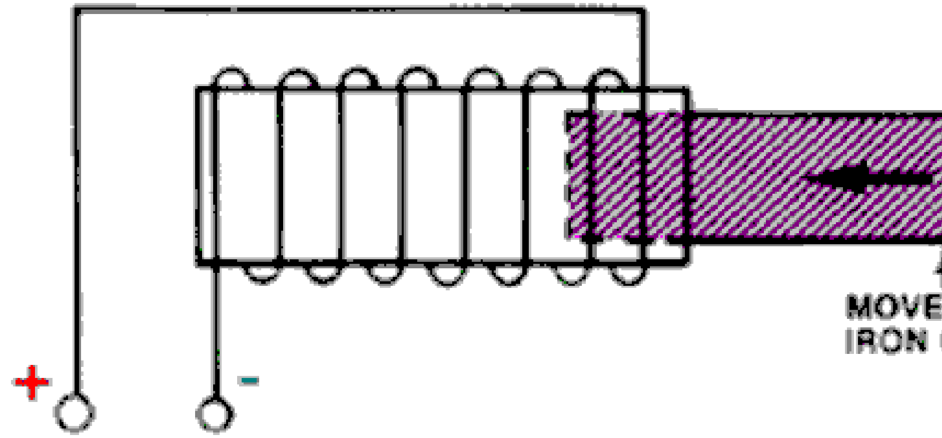
We implemented options 2 & 3. Using these representations we can show the following important properties of a central magnet + current loop.

- Stability—what is the force between magnet and RC?
- Scaling—how do the currents affect the B-field scaling?



Stability: Loop around Dipole

- When an automobile starter solenoid is energized, a magnetic material is pulled into the coil. Likewise RC.



- We compute the force between a current loop and a dipole field, "m" a distance "a" from the dipole. Two displacements are considered, moving the current loop up, out of the plane, and displacing it sideways, in the plane.
- $Fz = \int di \times B(a,z) = Im/(a^2+z^2)^{3/2}(-3\mathbf{z})$
- $Fx = \int di \times B(a+\mathbf{x},0) = Ima^2/(a^2+x^2-2ax)^{5/2}\ (-\mathbf{x})$
- Thus Hooke's law holds for either displacement, demonstrating unconditional stability

Stability: Dipole in RC

Or we can compute the force between a point dipole of moment, **m**, and a RC field at origin, **B**(0,0), using the analytic approximation to the elliptic integral valid only near the origin. (This is NOT the same problem!)

F = grad(m*B) = m **grad**(Bz)

$B_z = \mu k^{-5/2}(a^2+z^2-2p^2-pa)$ where

$k = (a^2+p^2+z^2+2ap)$

$\mu = \pi I a^2/c$,

hen,

$F_p = m\mu k^{-7/2}[-6a^3-16pa^2-6a(z^2-p^2)-9pz^2+p^3]$ ➔stable for p<

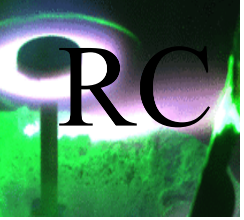
$F_z = m\mu k^{-7/2}[-3a^2z+9zap+12zp^2-3z^3]$➔stable for $pz<a^2$

Other stability issues

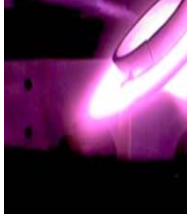
It is reassuring that the two approaches give the same answer. However, the real RC is not an ideal current ring but distributed over space. And the real spacecraft is not point dipole at the origin. And the real field is a sum of both RC and dipole fields. Note: $|B|^2 < B_d^{\ 2} + B_{RC}^{\ 2}$

If we start from a dipole field around a finite sized magn and turn up the RC, we first reduce the field inside the ring, and eventually reverse its direction, causing the magnet to experience a plasmoid-like force which destabilizes it in the z-direction, though stabilized in x.

Calculating how much RC will destabilize requires numerical modelling beyond the scope of this study. (e.g Sheldon 1991 modelled diamagnetic cavities in cusp.)

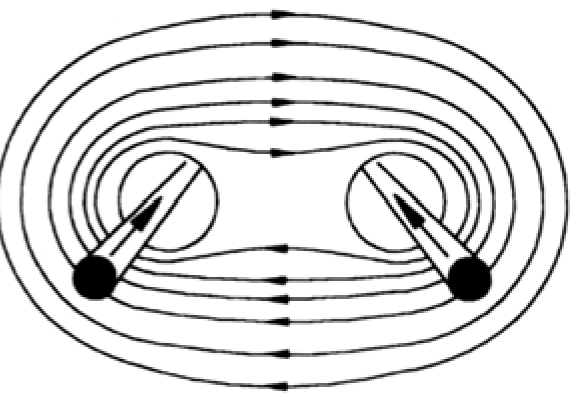


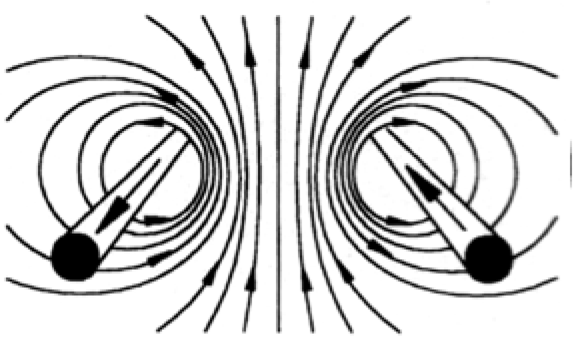
RC Radius Scaling

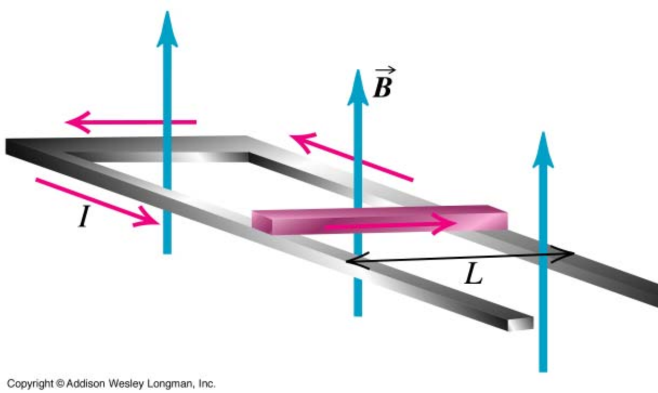


So far we have treated the RC as a rigid ring. Plasma currents are anything but rigid. Symmetry suggests that the current will be circular but what determines the radius?

Imagine a tangle of #22 gauge magnet wire on the table, through which we suddenly put 1 A of current. What happens? The wire expands into a circle. Why? Opposite currents repel.







Likewise an RC will expand outwards under self-repulsion, whic is only restrained by the i x Bd inward force of the central magne Steady state is reached when these are in balance

Scaling: Force Balance

The inward force has been calculated before:

– $F = i \times B_d(a,0) = im/a^3$

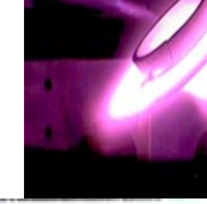
The outward force requires the self-induced B-field at the locatio
of the current. Even for an infinitely thin wire, we can estimate th
as the average of the field just inside and outside the wire, and
taking the limit as R=>a. Using the spherical harmonic expansio
(3), this limit exists and is finite, though convergence is very slo

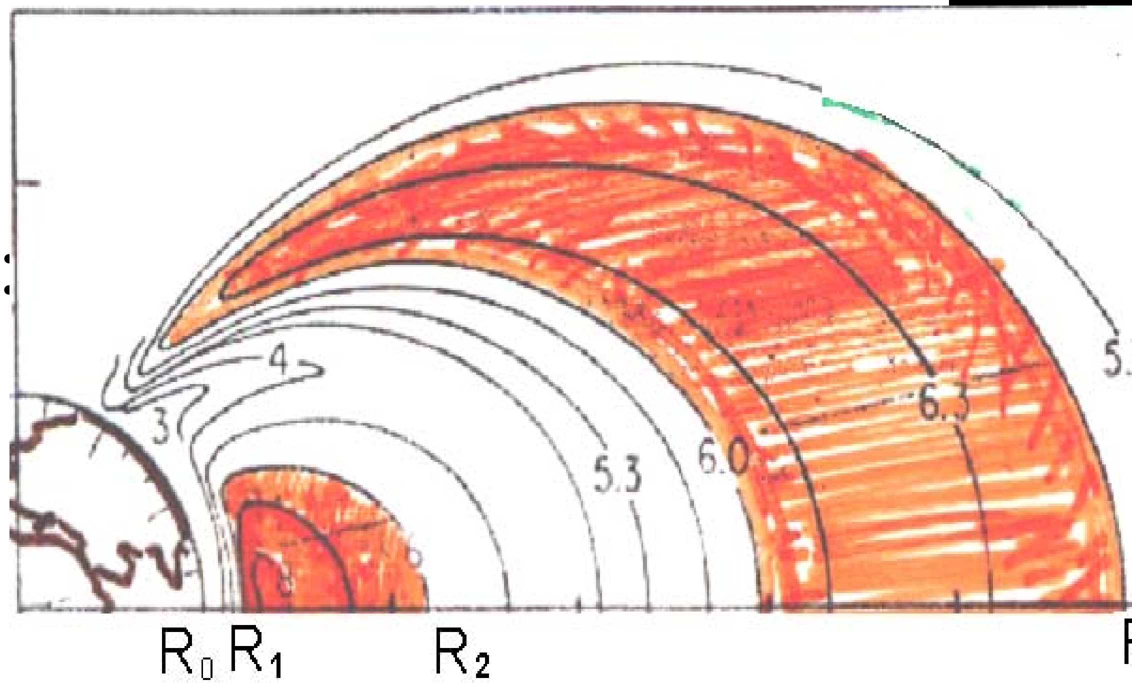
– $B_{rc}(a,0) \sim B_{rc}(0,0) = \mu/a^3$, so $F = i \times B_{rc} = i\mu/a^3$

Then equating the forces, means $m = \mu$. Using the definition that $m \sim iA$, and for a solenoid $B \sim iN$, we get

– $B_d R_0^{\,2} = B_{rc} a^2 \Longrightarrow B_d/B_0 = (R_0/R_2)^2$

Bubble Scaling





We define 3 regions:

Between magnet & RC:

– $B_1 = B_0 (R_0/R_1)^2$

Inside the RC itself:

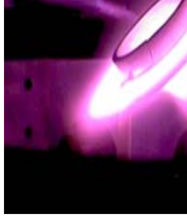
– $B_2 = B_1 (R_1/R_2)$

Outside the RC (viewing it as a vacuum dipole, radius=R

– $B_3 = B_2 (R_2/R_3)^3$

It is the radial extent of region 2 that is controversial. Ou contention is that *even if region 2 is reduced to a wire, a large magnetic bubble is obtained.*

Bubble Sizes



Without extended plasma current ring, $R_1 \rightarrow R_2$. Assumin the RC is found ½ way inside the bubble, so $R_2 = R_3/2$, th

$B_0 = B_1(R_1/R_0)^2 = B_2(R_2/R_0)^2 = B_3(R_3/R_2)^3(R_2/R_0)^2 = B_3(2R_3{}^2/R_0{}^2)$

If $B_0 = 1T$, $R_0 = 1m \rightarrow R_3 =$ 3.8 km

This is ¼ of the size predicted by Winglee, as a worst-ca scenario without 1/r scaling anywhere, yet R>100m. We should expect large bubbles from plasma currents.

Assume $R_1 = R_3/4$, $R_2 = R_3/2$, similar to Earth's RC.

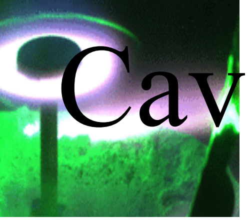
$B_0 = B_3(R_3/R_2)^3(R_2/R_1)(R_1/R_0)^2 = B_3R_3{}^2/R_0{}^2$

If $B_0 = 1T$, $R_0 = 1m \rightarrow R_3 =$ 5.3km

Assume $R_1 = 0.1R_3$, $R_2 = 0.9R_3$ then

$B_0 = B_3(.1234)R_3{}^2/R_0{}^2$

If $B_0 = 1T$, $R_0 = 1m \rightarrow R_3 =$ 15.2km



Caveats

This is a back-of-the-envelope calculation, intended to develop some intuition regarding magnetic bubbles. If it achieves order-of-magnitude accuracy it is doing well.

We don't have a BOE theory for Region2. There are man other forces acting on plasma besides the ones considere here. Diffusion is known to be important at Earth, convection and Rayleigh-Taylor play a part in Jupiter's magnetodisk. All these are expected to redistribute the pressure profiles from these cartoons.

The key point of this study is to stress that plasma curren DO increase the diameter of a magnetic bubble, and simultaneously provide a container for charged dust.

Conclusions

Our knowledge of plasma physics can be used to revive the magnetic sail approach, by using the plasma to create ring current much larger than the spacecraft itself. Basic physics considerations shows that large bubbles are likel

The discovery of magnetically trapped dusty plasmas car greatly improve the characteristics of a plasma sail. Muc basic physics needs to be understood before extrapolatio to space, but initial estimates suggest improvements as much as 200% on the plasmasail thrust.

Dusty plasmasail technology would enable missions suck as a polesitter or a storm monitor, and while system stud have yet to be done, they may be competitive with currer lightsail technology.